Electron Beam Momentum Measurements at PITZ

Results of my summerstudent time at DESY Zeuthen

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Abstract

PITZ does research and development of electron beam sources. Production and measurement of beam properties are described briefly. The momentum and momentum spread measurements are covered in more detail, together with the software to control it. My task was to extend this software. It consumed most of my time and only few measurements were done. No time was left for simulations on beam dynamics. Returning to Zeuthen to finish this work is planned.

Contents

1 Introduction to PITZ

The Photo Injector Test facility at Zeuthen (PITZ) does research and development of electron beam sources with small emittance and short bunch length, as required for FEL operation. The electron gun for FLASH (Free electron LASer Hamburg) has been characterized[1] at PITZ and is already in operation. For the next generation free electron laser XFEL a beam of even better quality is required. A future task will be characterizing the electron source for the International Linear Collider (ILC).
The challenge for experimentalists is twofold, since it is both difficult to produce the beam and to measure its properties. Both of these tasks are addressed by the team of physicists and engineers working at PITZ. The basic principles of beam production and the experimental setup will be described briefly in this section. A short overview over the different devices for measuring the beam properties will be given in section 2.

1.1 First experimental setup (until 2004)

Packets of electrons ("electron bunches") are produced by hitting a photocathode with a pulsed laser beam, making use of the photoelectric effect. To create an actual beam, the electrons then have to be accelerated. Simple as this might appear, these two sentences already impose a lot of physical questions: How should the laser pulse look like? What should the cathode be made of? What device can do the acceleration? How to focus the beam? Extensive research and development has been done to answer each of these questions. In addition, there are also many technical problems in actually realizing the experiment, e.g. how to keep the temperature of the system stable, or how to produce and maintain the ultra-high-vacuum which is required for the traveling electrons.

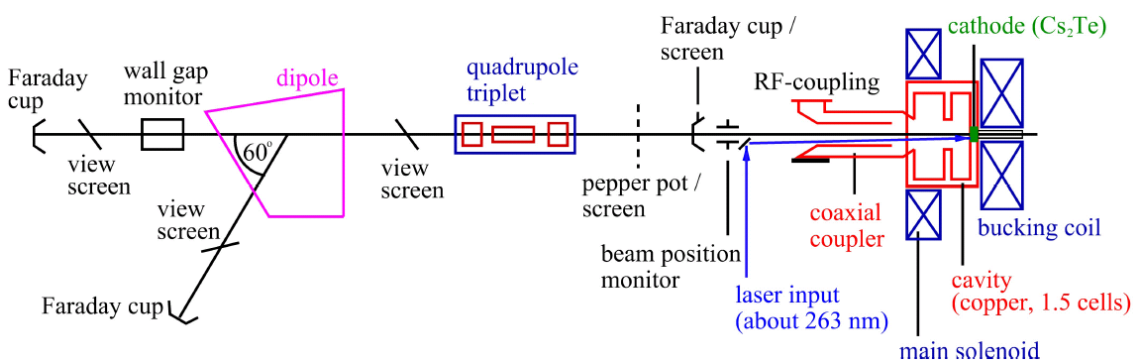

Figure 1: Schematic view of PITZ (from [3])

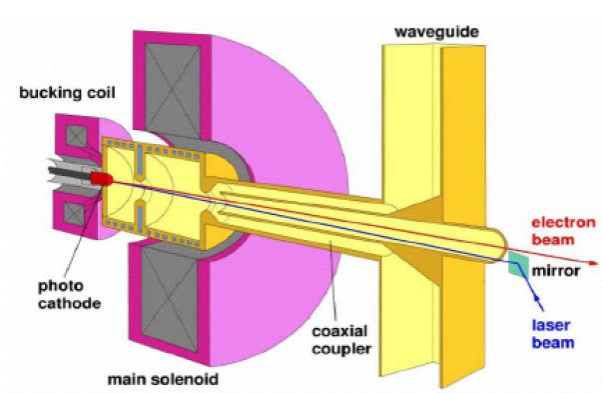

Figure 2: Schematic view of electron gun (from [1])

[1] i.e. its properties have been measured and setup parameters have been optimized.

Take a look at figures 1 and 2. The cathode laser[2], which is produced in a different room, is guided by mirrors and hits the photocathode[3]. A space charge cloud with a profile very similar to that of the laser pulse emerges. As mentioned above, those electrons have to be accelerated. This acceleration has to take place immediately, because otherwise the repelling Coulomb force would drive the electrons apart ("space charge effect"). For relativistic electrons this effect is not so strong, since they also feel a magnetic force which compensates the repulsion[4].
The electric field needed for acceleration is provided by the so called gun-cavity. It is a 1.5 cell L-band cavity with a coaxial RF (radio frequency) coupler. The radio frequency, which carries a power of several MW, is produced by a klystron in a separate hall and transported to the cavity using waveguides. Inside the cavity, it produces an oscillating standing wave field: $E = E(z) \cdot \sin(\omega t - \phi_0)$. The offset ϕ_0 is called launch phase, it describes the timing of laser pulse arrival and electric field oscillation. If the launch phase is chosen correctly, this results in an acceleration of the electron bunch to an average momentum of about $p_{mean} = 5.2$ MeV/c for a (typical) electric field gradient of 45 MV/m. This process is illustrated in figure 3.

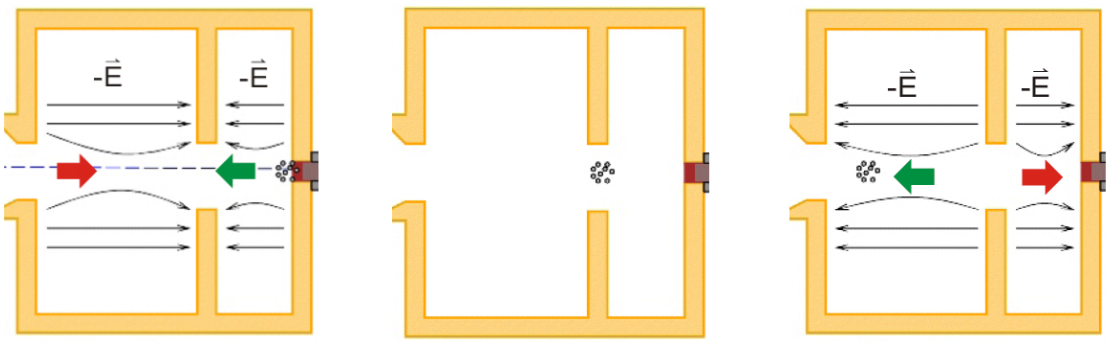

Figure 3: e^- bunch being accelerated in the gun cavity. This process takes about 0.5ns. Since the electron is charged negatively, the negative field ($-\vec{E}$) is sketched (from [1], modified)

The optimal choice of launch phase ϕ_0 is *not* such that laser-pulse and maximum electrical field coincide, but the laser pulse has to arrive earlier – otherwise the electrons lag behind and don't reach the cell division in time. The value of ϕ_0 can not be adjusted directly, instead one adjusts the so called set point phase $\Phi_0 = -\phi_0 +$ offset . This offset has to be determined by comparing measurements and simulation data. The optimal launch phase for a field gradient of 42 MV/m is found to be at 38° (see figure 4).

One device in figure 2 remains to be explained: the pair of solenoid magnets, which are called main and bucking solenoids. The main solenoid serves as an electronic lens and as such compensates space charge effects by refocusing the beam. This focus has to be adjusted depending on the beam energy and bunch charge. The task of the bucking solenoid is to compensate the magnetic field on the cathode surface – it's current is always set to a constant fraction of the main magnet current.

1.2 PITZ 2, major extension

To meet the even higher requirements for an X-Ray free electron laser, the emittance of the beam has to be even smaller ($\sqrt{\epsilon_x \cdot \epsilon_y} \leq 1.0\pi$ mm mrad). To make such an improvement possible, the PITZ facility had to be extended by an additional booster cavity and new measuring devices. To accommodate the new equipment, the PITZ tunnel had to be enlarged. Figure 5 shows a sketch of the new setup.

[2] You can find information about laser-pulse shaping in the report of my colleague Irakli Martashvili.
[3] Most photocathodes used at PITZ are made of Cs_2Te. Molybdenum is used for testing purposes.
[4] At speed of light, attraction and repulsion would cancel exactly.

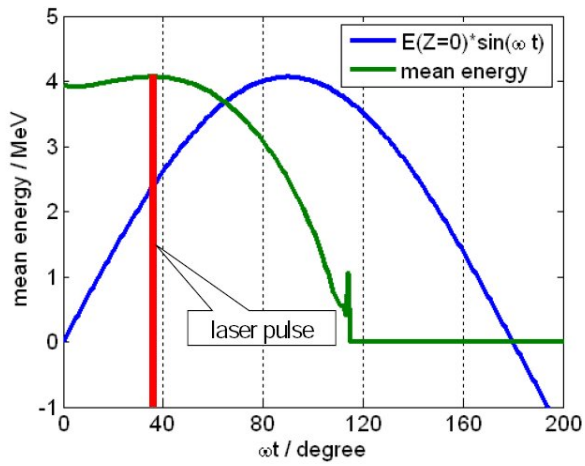

Figure 4: Mean electron energy for different launch phase. To get a high momentum, a choice of 38° is appropriate (field gradient of 42 MV/m). Above 120° no beam is produced anymore. In experiments, this curve is always shifted by some offset (from [3])

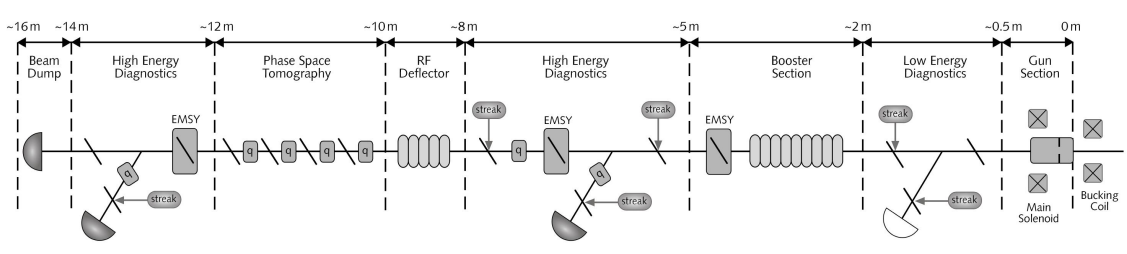

Figure 5: Overview over the PITZ facility. In the beginning, the facility consisted only of Gun Section and Low Energy Diagnostics (from [1])

2 Measurement of beam properties

2.1 Overview

The **transversal laser pulse profile** is measured using a virtual cathode (figure 6a). Measuring the **longitudinal laser pulse profile** is done using streak cameras: The laser beam hits a photocathode and produces electrons. To transform the temporal distribution into a spatial distribution a periodically rising electric field is applied – electrons in the later part of the beam are diverted more strongly and hit the screen further to the top. In figure 6b one can also see that the profile used at PITZ is close to being rectangular, with a rise and fall time of about 7ps. It has been shown that the beam emittance resulting from such a profile is lower by a factor of about 2 in comparison to a simple Gaussian profile. The setup which shapes the rectangular laser pulse was developed by the Max-Born-Institute Berlin and installed at PITZ in June 2003.

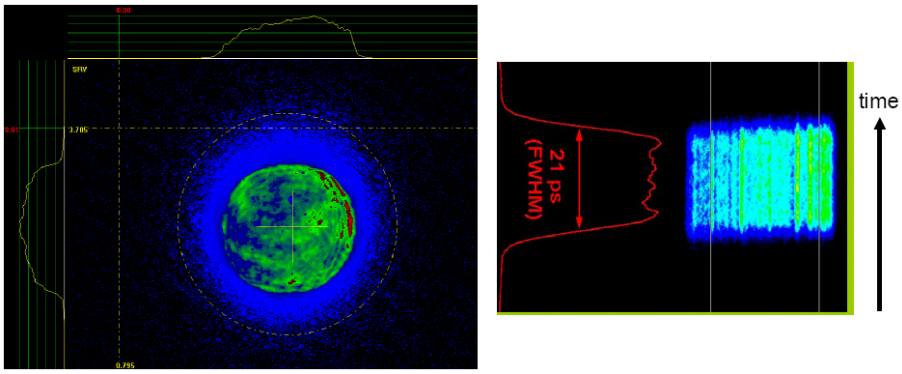

Figure 6: Laser pulse profile: a) transversal, obtained with virtual cathode b) longitudinal, obtained with streak camera (from [1])

Shape and size of the electron beam can be determined by means of fluorescent YAG (Yttrium-Aluminum-Garnet) screens and CCD cameras. The typical (RMS) size for a properly focused beam is 0.2-4mm. The **beam position** is measured with beam position monitors (BPMs), which locate the beam using the signal induced by passing electrons, and are thus non-destructive. The **bunch charge** is obtained by collecting the electrons in a Faraday Cup. 1nC ($\approx 10^9$ electrons) is a typical value and is also suitable for FEL operation. For non-interceptive beam-current measurements an Integrating Current Transformer (ICT) will be used. The **bunch length** is measured with streak cameras.
One of the most important measuring devices is the emittance measurement system (EMSY). EMSYs are installed at the beginning and the end of the beam-line ($z = 4$m and $z = 12$m) as well as at the point of lowest emittance ($z \approx 6$m). The main method for measuring emittance is using a mask of slits or holes (pepper pot), which divides the beam in small "beamlets". In about 2m distance those beamlets hit a screen, and again the picture is read out by a CCD-camera. From the size of the original beam and the sizes of the beamlets one can then calculate the emittance (see also figure 7).

2.2 Momentum And Momentum Spread Analysis

The normalized emittance is proportional to the momentum in logitudinal direction. Because of this, accurately determining the momentum is important. Another aim of the optimization process is to achieve a reasonably[5] short bunch length. Obviously, a low spread of electron momenta is required for this, and so measuring the momentum spread is interesting as well.
The experimental setup to measure the average momentum and the momentum spread of the electron bunch will be explained now. Afterwards, the software which communicates with the experiment and evaluates

[5] If bunches become too short, it is impossible to compensate the initial space charge effects. Instead, one lets the (reasonably short) relativistic electron bunch pass through a bunch-compressor (an arrangement of dipoles) later on.

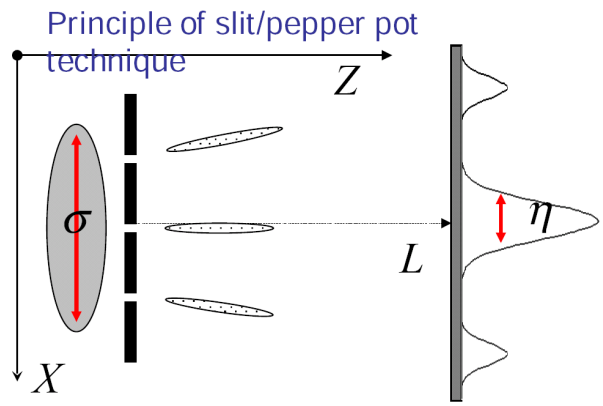

Figure 7: EMSY principle (from [1])

the collected data is described in some detail. Improving this software was the main part of my work as a summerstudent, so the current version of the software is described in some detail. The next section then will deal with the actual improvements.

2.2.1 Experimental Setup: The dispersive arm

A dipole magnet deflects the beam from its original direction into the so called dispersive arm. It is easy to see that the radius of curvature is inversely proportional to the strength of the magnetic field in the dipole and directly proportional to the electron momentum. Because of the latter, the continuos spectrum of momenta present in the electron beam results in a stretched pattern, which can be observed on a YAG-screen inserted in the dispersive arm. This pattern can be read out by a CCD-camera and then evaluated. Figure 8 shows a photo of the experimental setup. Figure 9 shows an exemplary pattern.

One major problem one can run into when measuring momenta is that the distribution might not fit on the screen. If the extension in bending direction is larger than the screen, then one has to take several pictures for different dipole currents (=different deflection strengths) and superpose them appropriately. If done for several momentum distributions, this process can take some time, because the dipole current cannot be adjusted arbitrarily: because of its hysteresis, the dipole current can only be changed in one direction, otherwise one has to start again from the lowest possible current to stay always on the same part of the hysteresis curve.
An even worse situation is to have a horizontal extension which is larger than the screen – parts of the beam then miss the screen and results will be inaccurate. This problem appears for example when the beam is focused very strongly in vertical direction, since this results in a weaker focus in horizontal direction.

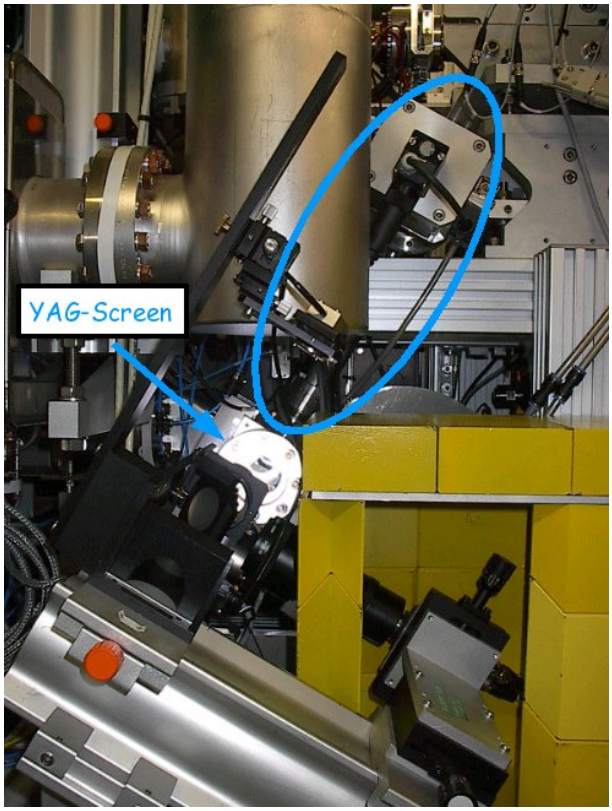

Figure 8: Experimental setup for momentum measurement. CCD-camera in front, YAG-screen behind the window (in vacuum). Area of the dispersive arm is highlighted.

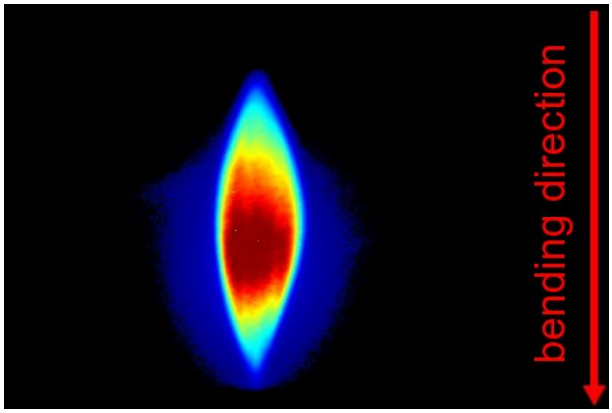

Figure 9: Electron beam on YAG-screen in the dispersive arm. Vertical direction coressponds to particle momentum (from [1])

2.2.2 Measuring tool: MAMA

The software for Momentum And Momentum spread Analysis carries the acronym MAMA [4]. Its current user interface is depicted in figure 10. Although the measurement routine described above is not too complicated, there are many subtleties to be taken care of. For beams which extend too large in the bending direction, MAMA provides a handy feature (called "Scan") to automatically take pictures for different dipole currents, merge them, and store them in one file. Of course, it also provides functionality for direct camera readout. In addition, it is possible to take a series of pictures and do statistical analysis, to get reasonable estimates for errors. There is always a certain amount of unwanted signal from dark current at the screen. To distinguish real signal and dark current, one has to close the laser shutter – then only dark current remains. Before each measurement, MAMA closes the shutter, takes background pictures of the dark current and opens the shutter again. The background pictures will be subtracted from the other pictures. If the beam is well focused, or if the pulse train duration is too high, some parts of the camera might reach saturation, also resulting in inaccurate results. MAMA detects when a certain saturation-threshold is crossed and then proposes to abort the current measurement.

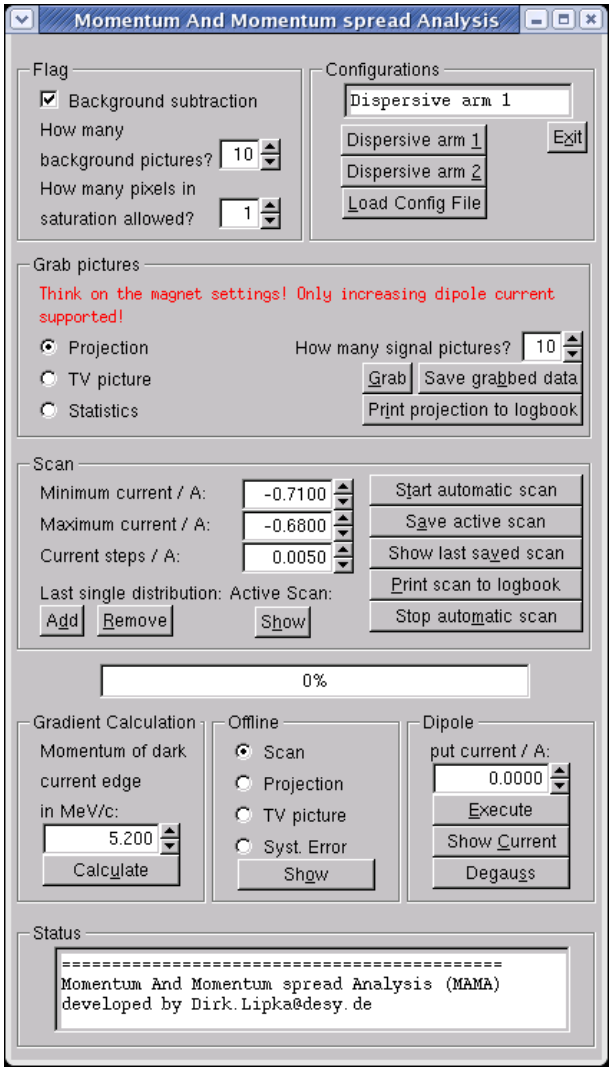

Figure 10: The graphical user interface of MAMA in its current version.

Information about the experimental setup has to be supplied to MAMA in a configuration-file. This file contains the commands to control dipole magnet and shutter, the position of the screen, timing information as well as some settings for the user interface. In figures 11 & 12 you find a camera picture and a distribution-

plot, which both have been created with MAMA.

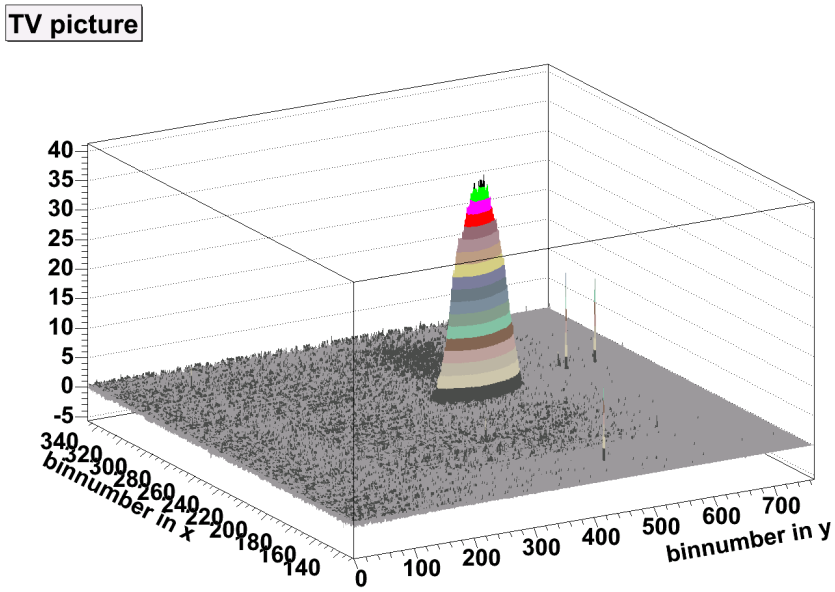

Figure 11: A picture which was taken directly from the camera...

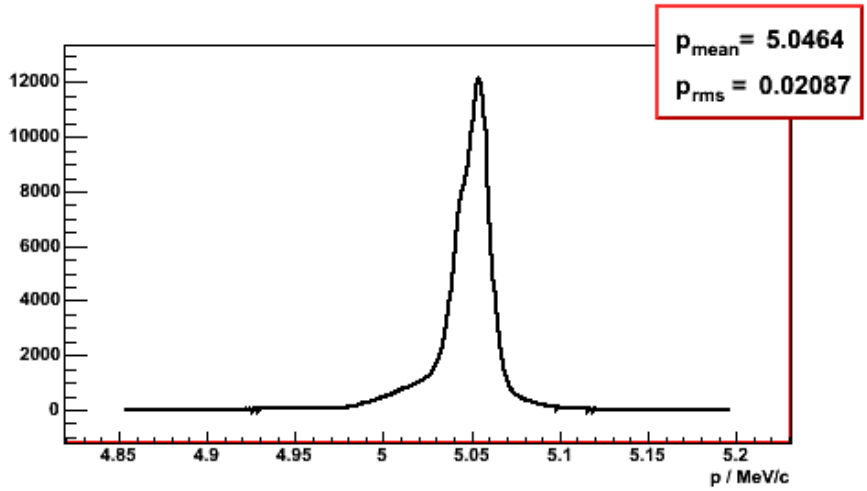

Figure 12: ... and its projection, which can directly be interpreted in terms of electron momenta.

3 Improving the software

Since MAMA is frequently used, it was obvious to ask how this program should be extended in the future. There were many small ideas, and one major improvement, which will be described in the next section.

3.1 Implemented changes

Often it is interesting to see how momentum and momentum spread change in dependence on some other parameter. At the moment, all parameters except the dipole current have to be adjusted using the PITZ control software. The person running the experiment has to use at least two programs simultaneously (PITZ and MAMA), which is inconvenient. The process of repeatedly adjusting the parameter and then measuring with MAMA is not too difficult but very time-consuming and thus an ideal candidate for making it automatic. As a first step towards such a tool, it was intended to implement a "Phase Scanner", which changes the RF phase angle over a given range with a certain step-size. The proposed layout is shown in figure 13.

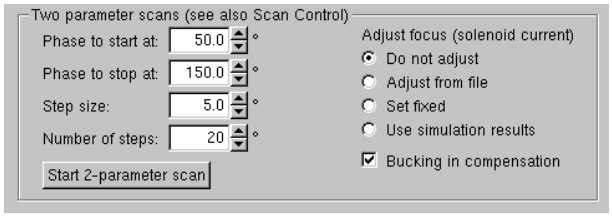

Figure 13: The proposed layout for the phase scanner. When changing the phase, also the focus has to be adjusted – but there is no obvious way in which to do that; most of the options are non-functional at the moment.

The next step would be a more general tool to adjust any parameter in this manner. The development appeared to be not too difficult and testing worked out fine, but when the program was tested under realistic circumstances, it produced wrong results. Up to now, this problem has not been fixed, further details can be found in section 3.2.

3.1.1 Minor changes

Three changes which are quite different in nature will be described here to give you an impression of how diverse the different tasks of MAMA actually are.

- It is sometimes useful to switch between different configuration-files, so a drop-down-list was added, where one can quickly select another configuration. It is easily possible to add new configurations to this list. In a similar manner, one can now switch between different camera-readout servers – in the old MAMA this kind of change required actually manipulating the value in a text file.
- Together with each momentum scan a file with information about the current status of PITZ is stored. The exact parameters which should be stored can be easily adjusted.
- When changing the dipole current, one has to be careful (especially when working in the high energetic dispersive arm), because it is possible to divert the beam to places where it might cause damage. To prevent many of these situations, the laser-shutter will be automatically closed when the dipole current leaves a certain range, and reopened again afterwards.

3.2 Problems

Most of the implemented changes appear to work correctly, although they should be tested in more detail. There are some suspicions about why the results of the phase-scan-tool turn out to wrong, but unfortunately there is no easy way to fix the problem. This is due to the fact that the old version of MAMA contained more than 5000 lines of code, which were not well structured and lacked comments, which slowed down my progress considerably. After acquiring an overview over the situation, it seems reasonable to rewrite the program completely. This is work for another 4-8 weeks, for which a return to Zeuthen is neccessary.

4 Some measurement results

Because of aforementioned problems, no real data was taken with the new MAMA features. To get some practice in working with PITZ and also to get a feeling for the difficulties and specialties of the measuring process, I took a phase scan by hand. To get an idea on how to focus the beam properly, different energies were selected by choosing different phases – as explained above, the beam energy depends strongly on the timing between laser pulse and RF. For those energies it was tried to position the mean momentum in the center of the screen – this can be done by adjusting the dipole current. In most cases one can determine by eye[6] if the beam is centered properly, although there are more accurate methods to do this. After finding the appropriate dipole current, the solenoid current was adjusted to focus the beam. Plotting the relation between I_{Dipole} and $I_{Solenoid}$ one finds a relation which appears to be linear in a certain range (figure 14). This can later be used to roughly find the right focus for the beam.

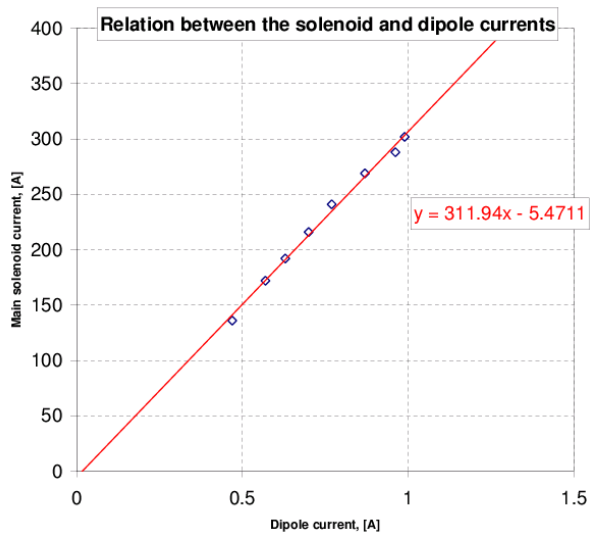

Figure 14: Relation between Dipole and Solenoid currents to achieve good focus

The phase angle was varied over the largest possible range and momentum measurements were taken. In figure 15 you can see the results. The obtained momentum spread was much too high[7]. For a fixed phase of 135° the solenoid current (i.e. the beam focus) was changed to find a small momentum spread, the resulting plot is shown in figure 16. To give you some more realistic result another plot is provided (figure 17), which is in good agreement with beam dynamic simulations.

[6] That is, by looking at the CCD camera picture, which is displayed on a computer screen – not by literally looking at the beam.

[7] This appears to be both the result of my lack of time and my lack of experience.

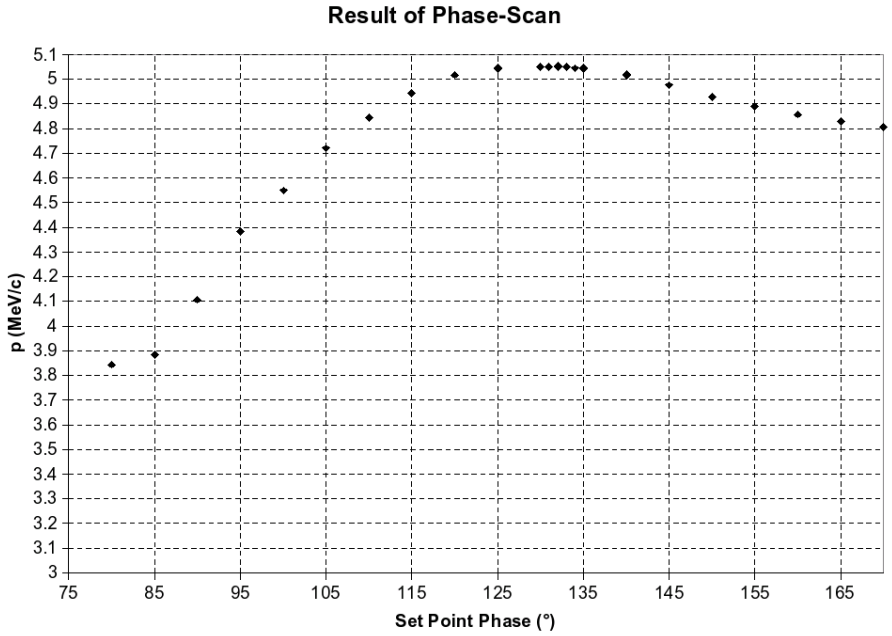

Figure 15: Rough phase scan. The beam sometimes was not properly focused, the obtained values for the momentum spread were much too big and are not shown here.

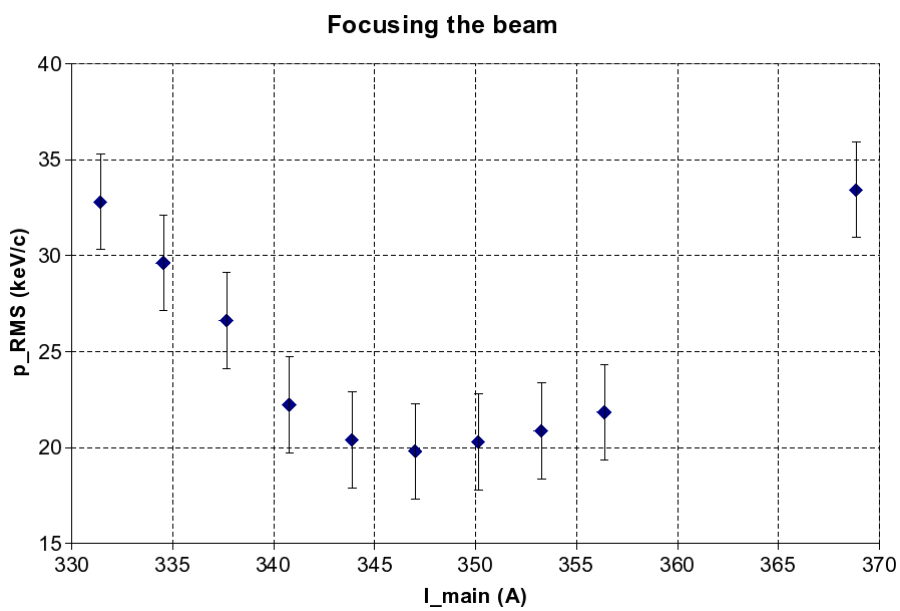

Figure 16: Different main solenoid currents result in different momentum spreads (fixed set point phase of $\Phi = 135°$).

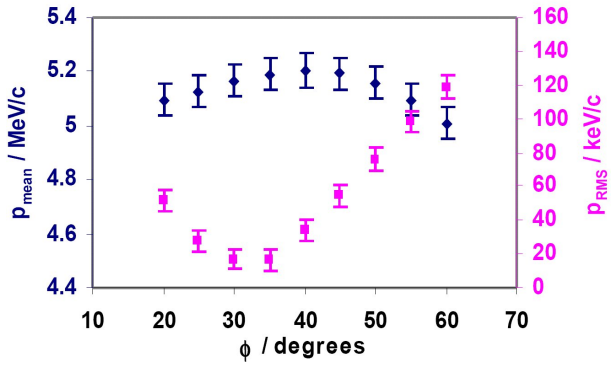

Figure 17: This plot of a more accurate measurement shows the mean momentum as well as the momentum spread (in a different scale!). It is interesting to notice that highest momentum and lowest momentum spread are close to each other.

5 Summary, Outlook

Some progress was made in the direction of improving an important measurement software at PITZ. Unexpected difficulties prevented the work from being finished in time, nevertheless the concept of the MAMA extension has been elaborated, including features which are time-saving, store additional information for later evaluation, and could also prevent damage on the facility. A return to Zeuthen to complete this task was requested and will probably be undertaken. It is still unclear how to optimally refocus the beam for different parameter-changes, which would also have to be done by the program. ASTRA-Simulations[8] on this subject are assumed to be helpful.

6 Acknowledgments

First of all I want to thank my supervisor Juliane Roensch for many ideas for improvement of MAMA and also for always having time for my questions. Thanks also to the other members of the PITZ-team for taking me up so kindly. I want to mention Mikhail Krasilnikov, Lazar Staykov and Bagrat Petrosyan for helping me with my work. Special thanks go to Frank Stephan, especially for offering me a Diploma Thesis at Zeuthen.

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Finally I want to mention Sabrina Harzer for repeatedly giving me telephone support and good advice on a variety of topics throughout my stay in Zeuthen. Thank you!

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[8] A Space charge TRacking Algorithm